

Life cycle environmental impacts of decommissioning Magnox nuclear power plants in the UK

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Abstract

Purpose Full life cycle assessment (LCA) impacts from decommissioning have rarely been assessed, largely because few sites have been decommissioned so that the impacts of decommissioning are currently uncertain. This paper presents the results of an LCA study of the ongoing decommissioning of the Magnox power plant at Trawsfynydd in the UK. These results have been used to estimate the potential environmental impacts for the whole UK Magnox fleet of 11 reactors that will have to be decommissioned during this century.

Methods The functional unit is defined as ‘decommissioning one Magnox power plant’. The system boundary considers all stages in the life cycle of decommissioning, including site management, waste retrieval, plant deconstruction, packaging and storage of intermediate- and low-level wastes (ILW and LLW). High-level waste, i.e. waste fuel is excluded as it was being removed from the site to be reprocessed at Sellafield. The environmental impacts have been estimated using the CML 2001 methodology. Primary data have been sourced from the Trawsfynydd site and the background from Ecoinvent.

Results and discussion Most impacts from decommissioning are due to the plant deconstruction (25–75 %) and ILW storage and disposal (25–70 %). For the example of global warming potential (GWP), estimated at 241 kt CO₂ eq./functional unit, or 3.5 g CO₂ eq./kWh of electricity generated during the lifetime of the plant, 55 % of the impact is from plant deconstruction and 30 % from ILW disposal. The results for the whole UK Magnox fleet indicate that the impacts vary greatly for different sites. For example, the GWP ranges from 0.89 to 7.14 g CO₂ eq./kWh. If the impacts from storage of waste fuel at Sellafield are included in the estimates, the GWP increases on average by four times. Overall, decommissioning of the UK Magnox reactors would generate 2 Mt of CO₂ eq. without and 11 Mt of CO₂ eq. with the waste from Sellafield. This represents 0.4 and 2 % of the total UK annual emissions, respectively.

Conclusions The impacts of decommissioning can vary greatly at different sites depending on the amount of waste and electricity generated by the plants. Delaying decommissioning to allow the energy system to decarbonise could reduce the environmental impacts, e.g. GWP could be reduced by 50 %. The impacts could also be reduced by reducing the volume of waste and increasing recycling of materials. For example, recycling 70 % of steel would reduce the impacts on average by 34 %.

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1 Introduction

There is currently an international drive to build new nuclear power plants, bringing about a ‘nuclear renaissance’. At the same time, a significant number of nuclear plants are coming to the end of their lifetime and will need to be decommissioned. In the UK, all but one of the present reactor fleet

will reach the end of their lifetime by 2023. At the time of writing, 14 nuclear power plants have either been closed down or are being decommissioned, including ten of the 11 Magnox¹ power plants. Decommissioning these plants and the related infrastructure is expected to cost UK £73 billion over the next 100 years (NAO 2008) and it could also cause significant environmental impacts.

The environmental impacts of the nuclear life cycle (Fig. 1) have been the subject of a number of life cycle assessment (LCA) studies (e.g. Fthenakis & Kim 2007; Lenzen 2008; Sovacool 2008; Vattenfall 2010a; Vattenfall 2010b; Simons & Bauer 2012). However, the full impacts from decommissioning have rarely been assessed, largely because few sites have been completely decommissioned (Fthenakis & Kim 2007; Jazayeri et al. 2008; van Leeuwen and Smith 2005). In the absence of data, most studies have considered either the energy required for construction of power plants (e.g. Voorspools et al. 2000) or decommissioning costs (e.g. van Leeuwen and Smith 2005) as a proxy for estimating the environmental impacts of decommissioning. These are usually expressed only in terms of CO₂ emissions and estimates have varied widely (Beerten et al. 2009). Therefore, the life cycle impacts of decommissioning remain uncertain.

In an attempt to provide a further insight into the subject, this paper presents the results of an LCA study of the ongoing decommissioning of the Magnox power plant at Trawsfynydd in the UK. These results are then used to estimate the potential environmental impacts for the whole UK Magnox fleet that will have to be decommissioned over the next decades.

2 Goal and scope of the study

The main goal of the study is to estimate the life cycle environmental impacts of decommissioning Magnox nuclear power plants. The functional unit is defined as ‘decommissioning one Magnox power plant’. The Trawsfynydd plant based in Wales and currently being decommissioned is used as a case study. This is discussed in Sections 2, 3 and 4. A further goal is to estimate the potential impacts of decommissioning of all Magnox reactors in the UK based on the results obtained for the Trawsfynydd plant. For these purposes, the second functional unit is defined as ‘decommissioning of the whole UK Magnox fleet’. This is the subject of Section 5.

¹ Magnox is a British-designed pressurised reactor, which uses natural (unenriched) uranium as fuel, graphite as moderator and carbon dioxide as coolant. Magnox (magnesium non-oxidising) alloy is used for cladding; hence the name. For description of Magnox reactors, see, e.g. (Jensen & Nonbøl 1999). Magnox reactors have only ever been used in the UK and are no longer built. The last Magnox plant is scheduled to close by September 2014.

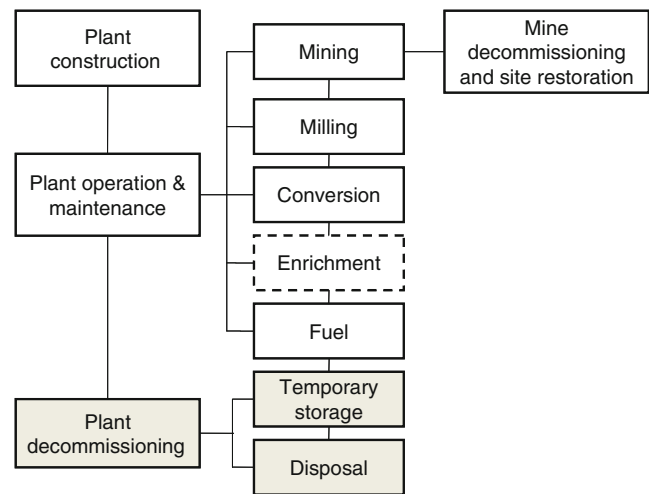


Fig. 1 The life cycle of nuclear power. The shaded boxes indicate the life cycle stages included in the decommissioning study considered in this study. For full detail, see Fig. 2. Fuel enrichment is not carried out for Magnox reactors

Two 390 MW Magnox reactors at Trawsfynydd based in the Snowdonia national park in North Wales operated for 24 years until 1993. The lifetime energy output of the site was 69 TWh (NDA 2006) and defuelling operations were completed by August 1995. Under the current decommissioning plans, all operational wastes and peripheral fixtures are currently being removed, with completion expected in 2015. Thereafter, the buildings housing the reactor cores will be sealed for a period of ‘care and maintenance’ (also known as ‘safestore’) lasting at least 70 years. During this time, no further decommissioning is carried out and no specific site management (other than periodic monitoring) is required. This will allow radioactive contamination to decay to lower levels, simplifying the final demolition and site clearance, which is scheduled to occur between 2088 and 2098 (NDA 2006).

Therefore, the system boundary (Figs. 1 and 2) includes all site activities after the completion of defuelling and comprises:

- Site management and research and development of decommissioning methods, which continue throughout the decommissioning period
- Waste retrieval
- Plant deconstruction, which involves dismantling and decontamination of the power plant structure as well as construction and demolishing of the supporting structures used for the deconstruction
- Separation of recyclable materials
- Packaging of waste
- Interim storage, transport and final disposal of wastes
- Land remediation.

Further description of these activities is given in the next section. Note that storage of spent fuel is excluded from the system boundary as it was being removed from the site for

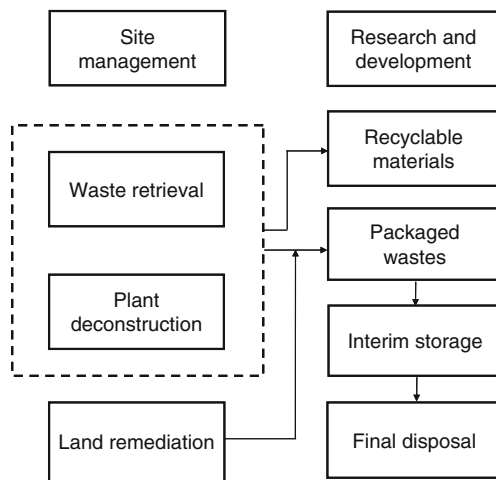


Fig. 2 System boundary for decommissioning

reprocessing at Sellafield throughout the lifetime of the power plant.

3 System description, assumptions and data

3.1 Site management

Site management will be required over 30 years to support early stages of decommissioning from 1995 to 2015 and then demolition from 2088 to 2098 (NDA 2006). No significant active site management is anticipated during the period of care and maintenance in between these two phases, so resource consumption in this period is considered negligible. Site management involves administrative and service functions such as surveying, planning, costing, time-tabling and approvals; in other words, typical office operations. Therefore, typical values for resource consumption in offices have been assumed in this study (Table 1), taking into account staff numbers and floor space (OGC 2009).

3.2 Research and development

Research and development (R&D) includes designing and testing new decommissioning techniques as well as further development of existing techniques (Verseemann 2008). In each case, test facilities or ‘dummy’ structures may need to be constructed. At Trawsfynydd, R&D includes trialling electrochemical treatment of radioactive oil (Magnox North 2010c), testing waste retrieval methods (e.g. Magnox North 2010a) and modification of tools and fixings to increase the speed and reliability of pond scabbling² (Magnox North 2009a, 2010b). As the R&D and active

decommissioning are similar in nature, they are assumed here to require similar but lower resources (as described in Sections 3.3 and 3.4) and for only a fraction of the time (see Table 1).

3.3 Waste retrieval

In UK, nuclear wastes are categorised into three types (Bayliss and Langley 2004):

- Low-level waste (LLW): waste with radioactivity levels not exceeding 4 GBq/tonne (alpha) or 12 GBq/tonne (beta/gamma), which are placed in managed surface disposal facilities
- Intermediate-level waste (ILW): waste with higher beta/gamma activity, potentially also some alpha emitters, whose heat production is sufficiently high to require managed disposal
- High-level waste (HLW): heat-generating wastes which require managed disposal.

Presently, ILW and HLW decommissioning wastes are placed in interim storage at each nuclear site until long-term disposal becomes available [for the UK (CoRWM 2006) and the European Commission (2010), preference is for a sealed facility, 500 m or more below the surface]. As already mentioned, no HLW will be generated from decommissioning the Trawsfynydd site as no spent fuel remains at the site. ILW or LLW will arise in decommissioning operations, depending on the initial level of contamination and subsequent treatment of the waste during decommissioning.

Waste retrieval involves recovery from the concrete vaults beneath the site buildings of materials, which were radioactively contaminated during the operation of the power plant. This is typically carried out using remotely controlled heavy machinery. Various wastes are recovered and treated separately, according to their material and radiological characteristics; however, the principal elements of all waste recovery are similar and involve:

- Accessing of waste, possibly requiring construction work
- Its mobilisation, if required, using jetting or stirring by pneumatic, mechanical or chemical means (IAEA 2006; IAEA 2007; Parsons 2007)
- Retrieval by manipulator arms or robotic vehicles with grabs, suction tools or pumps (IAEA 2006; IAEA 2007; Wall & Shaw 2002)
- Transfer to waste processing by winches, hoist and conveyors (Wall & Shaw 2002).

Retrieval of the following five types of waste is carried out concurrently at Trawsfynydd (Parsons 2007) and will continue for approximately 10 years (NDA 2006):

² Scabbling is the process of abrading the surface of concrete in the ponds with a rotating drill head to remove contamination.

Table 1 Equipment and resource used for site management and R&D over 30 years

Life cycle stage	Equipment/resource	Included in the study	Use	Quantity/size	Assumptions	Source	LCA data source (age), region ^f
Site management					350 staff (average) over 30 years ^a 2 MWh per person per year ^b	Own estimate ^a	
	Electricity	Electricity generation	Electricity used in offices and administrative buildings	8,118 GJ		Own estimate ^b	Ecoinvent (2002), UK
	Tap water	Production of tap water	Water used in offices and administrative buildings	225 million litres	50 l per person per day	British Water (2011)	Ecoinvent (2000), Eur
	Paper	Material manufacture	Retained documents	110 tonnes	10 % of office paper use	Hawken et al. (1999)	Ecoinvent (2000), Eur
	Waste:	Material manufacture	Materials used in normal office operation	1,580 tonnes	150 kg per person per year ^c	Own estimate ^c	
	Paper/card		Paper and card	1,100 tonnes	70 % of waste ^d	Own estimate ^d	Ecoinvent (2000), Eur
	Organics		Food wastes	250 tonnes	16 % of waste ^d	Own estimate ^d	Ecoinvent (2000), Eur
	Plastic		Packaging and plastics	80 tonnes	5 % of waste ^d	Own estimate ^d	Ecoinvent (2000), Eur
	Glass		Glass	60 tonnes	3.5 % of waste ^d	Own estimate ^d	Ecoinvent (2000), Eur
	Metal (Al)		Metals, assumed tins/cans	50 tonnes	1.5 % of waste ^d	Own estimate ^d	Ecoinvent (2002), Eur
Research and development							
	Building	Construction of small contained area	Small purpose-built research facility	50 m ²	Reasonable area for experimental work	Own estimate	Ecoinvent (2001), CH
	Electricity	Electricity generation	Electricity used in testing	756 GJ	7,000 h at 30 kW ^e	Own estimate ^e	Ecoinvent (2002), UK
	Electronics	Material manufacture	Experimental control and monitoring systems	0.1 tonnes	Fewer control systems required than actual decommissioning	Own estimate	Ecoinvent (2005), Eur
	Heavy machinery	Construction of machinery	Equipment used in testing new methods	5 tonnes	Weight of a typical decommissioning machine ^e	Own estimate ^e	Ecoinvent (2001), Eur

^a Based on 200 permanent staff and half the current 300 temporary or contract staff during early stage decommissioning (1995–2015) and demolition (2088–2098) (NDA 2006)

^b Within estimated range based on 10 m² floor area (OGC 2009) and 100–kWh/m² (CIBSE 2000)

^c Based on the range of 125–200 kg per person (PACE 2000; Hilton undated; Mouchel 2010)

^d Based on office waste data from Resource NSW (2002) and Waste online (2004)

^e Based on a 5 tonne, 30 kW ‘Brokk’, a typical remote control vehicle used in decommissioning

^f LCA data considered applicable to UK, Switzerland (CH) or Europe (Eur)

- Miscellaneous activated components (MAC): metal and wire, which have become radioactive (activated) following exposure to radiation
- Fuel element debris (FED): fragments of the magnesium oxide alloy casings from uranium fuel rods and potentially also fuel debris, removed when preparing the fuel for reprocessing
- Active waste vaults (AWV): various contaminated items, including rags, paper, metals and asbestos cladding from operations and maintenance work
- Resins: ion-exchange resin used to clean and decontaminate components during the power plant operation
- Sludges: liquid wastes from the cooling ponds and effluents, containing corrosion products from Magnox fuel

rods and other materials such as grit, paint flakes, oils and grease.

Data and assumptions for the waste retrieval stage related to the use of machinery and waste quantities can be found in Tables 2 and 3, respectively.

3.4 Plant deconstruction

3.4.1 Dismantling and decontamination

Dismantling of nuclear power plants involves the removal and possible decontamination of recoverable structural elements such as walkways, fences and cabling and finally the demolition of structures. With on average 160,000 and 40,000 t, concrete and steel are respectively by far the largest components of the structure of a nuclear power plant (Bryan & Dudley 1974; White & Kulcinski 2000). The estimates for Trawsfynydd waste (NDA 2007) indicate that approximately 80,000 t of concrete and 13,500 t of steel will be consigned as radioactive waste upon final demolition.

It is also estimated that 30,000 t of steel will be available for recovery and recycling (see Table 3). The other major waste component is the graphite moderator of the reactor core, amounting to 3,500 m³ of mostly ILW, which must be removed prior to demolition.

All steel and other metalwork must be cut for removal, transport, packaging for disposal and/or recycling. Data for metal cutting at Trawsfynydd are not available; however, detailed calculations describing the cutting required to extract and dispose of 21 tonnes of pipe-work and vessels from a small (250 m³) nuclear industry facility have been obtained from Sellafield (as confidential information) and used in this study. Although the facilities differ, the requirements for packaging and disposal of the material are assumed to be the same and hence also the necessary cutting regimes for the steelwork. These have been extrapolated for the total amount of 43,500 t of steel assumed in the study (13,500 t as radioactive waste + 30,000 t available for recycling).

Up to 80 % of metalwork requires some decontamination (Steiner, 20 December 2010, by email), mostly

Table 2 Equipment and resources used for waste retrieval, scabbling² and decontamination over the lifetime of decommissioning

Infrastructure component	Equipment/resource	Included in the study	Use	Quantity	Assumptions	LCA data source (age), region ^c
Ventilation	Ventilation unit (720 m ³ /h)	Manufacture, transport, operation and disposal of unit	Ventilation and vacuum/pressure systems operations	500 m ² years	50 m ² space, ventilated for 10 years ^a	Ecoinvent (2003), CH
Electronics	Electronics for control systems	Manufacture and transport of electronics	Control systems and devices for site safety, operations and monitoring equipment; including fire safety, CCTV, robotic and remote control systems	1 tonne	All high-tech electronic equipment consists of similar material components	Ecoinvent (2005), Eur
Heavy machinery	Heavy equipment	Manufacture	Remote vehicles, cranes, hoists, grabs, conveyors for waste handling	10 tonnes	Two 5-tonne remote control machines ^b	Ecoinvent (2001), Eur
Electricity usage	Electricity	Electricity generation	Consumption by all electronic and mechanical machinery	3.77 TJ	30 kW per heavy machine ^b 5 kW per tonne of electronics ^c	Ecoinvent (2002), UK
Routine cleaning	Electricity and water	Electricity generation and tap water production	Power and water used in routine decontamination of staff and equipment	54 GJ	4 kW washing machine ^c	Ecoinvent (2002), UK
				8.8 million litres of water	8 kW shower unit ^c Water consumption of domestic machines ^{c,d}	Ecoinvent (2000), Eur

^a Estimated average size of typical cells and vaults

^b Based on a 5-tonne, 30 kW Brokk, a typical remote-controlled decommissioning vehicle

^c Based on observed consumption of typical consumer electronic products

^d Water estimate includes an allocated share based on water consumption at Trawsfynydd in 2004 (NDA 2010a)

^e LCA data considered applicable to UK, Switzerland (CH) or Europe (Eur) cases

Table 3 Summary of resources used for decommissioning and waste management

Life cycle stage	Process/tool/material	Use	Quantity	Assumptions	Source	LCA data source (age), region ¹
Waste retrieval	Typical decommissioning equipment and resources	Decontamination operations	See Table 2	Typical equipment and resource used in decommissioning	Own estimate	See Table 2
Decontamination	Typical decommissioning equipment and resources	Decontamination operations	See Table 2	Typical equipment and resource used in decommissioning	Own estimate	See Table 2
	Soap	Decontaminant	5 tonnes	1 l per 3 m ³ of metal	Own estimate	Ecoinvent (1995), Eur
	Tap water	Decontaminant	8,800 tonnes	Known site water use, allocated amongst decommissioning operations	NDA (2010a)	Ecoinvent (2000), Eur
Construction and demolition of temporary structures and demolition of plant	Transport (20 tonne lorry)	Movement of materials	500,000 km	500 × 50 km journeys per year ^a	NDA (2010a)	Ecoinvent (2003), Eur
	Concrete	Demolition and disposal of demolition waste	80,000 tonnes	Assumed to be uncontaminated waste based on 160,000 tonnes of concrete in a typical plant	Bryan & Dudley (1974)	Ecoinvent (2000), GLO
	Excavation	Landscaping and backfilling	70,000 m ³	Equivalent to concrete volume	Own estimate	Ecoinvent (2001), Eur
	Concrete	Construction	2,000 tonnes	100 tonnes per year ^a	NDA (2010a)	Ecoinvent (2001), CH [†]
	Electricity	Tool use	9,690 GJ	50 kW/ft ² for building 50,000 m ²	Arnold (2008)	Ecoinvent (2002), UK
	Steel	Construction	4,000 tonnes	200 tonnes per year ^a	NDA (2010a)	Ecoinvent (2002), CH [†]
Cutting	Typical decommissioning equipment and resources	Cutting operations infrastructure	See Table 2	Typical equipment and resource used in decommissioning	Own estimate	See Table 2
	Power saws	Cutting tools	5	Typical metal saws, 2–7.5 kW	Own estimate	Ecoinvent (2001), Eur
	Electricity	For cutting	1,260 GJ	100,000 h based on steel volume ^b	Own estimate	Ecoinvent (2002), UK
Graphite retrieval	Typical decommissioning equipment and resources	Decontamination operations	See Table 2 ^c	Typical equipment and resource used in decommissioning	Own estimate	See Table 2
Scabbling	Decommissioning resource (Table 2)	Concrete scabbling operations	See Table 2	Basic safety and machinery requirements for decommissioning operations	Own estimate	See Table 2
Recycling	Steel (electric furnace)	Steel recycling	30,000 tonnes	Potentially recoverable for recycling ^d	Parsons (2007)	Ecoinvent (2001), Eur
Interim storage	Concrete	Building store	13,333 m ³	Concrete used in Trawsfynydd ILW store	Magnox North (2009b)	Ecoinvent (2001), CH [†]
	Steel	Building store	1,770 tonnes	Modified Ecoinvent data ^e	Dones et al. (2009)	Ecoinvent (2002), CH [†]
	Transport rail	Movement of materials	735,000 tkm	Modified Ecoinvent data ^e	Dones et al. (2009)	Ecoinvent (2000), Eur
	Road transport	Movement of materials	42,300 tkm	Modified Ecoinvent data ^e	Dones et al. (2009)	Ecoinvent (2005), CH
	Diesel	Construction machinery	6,120 GJ	Modified Ecoinvent data ^e	Dones et al. (2009)	Ecoinvent (2001), GLO
	Electricity	Construction use	972 GJ	Modified Ecoinvent data ^e	Dones et al. (2009)	Ecoinvent (2002), UK
	Disposal concrete	Demolition of store	33,700 tonnes	Modified Ecoinvent data ^e	Dones et al. (2009)	Ecoinvent (2002), CH
ILW disposal	Final Repository	Building, filling, closing deep repository	13,200 m ³	UK repository design for 168,000 m ³ of ILW is used to scale the reference Swiss design	Nirex (2003); Dones et al. (2009)	Ecoinvent (2002), CH [†]
	Electricity	Running storage facility	25,000 GJ	0.5 TJ/year ^f	Chan et al. (1998)	Ecoinvent (2002), UK
LLW disposal	LLW treatment	Excavation for construction of store	75,000 m ³	Surface storage	Dones et al. (2009)	Ecoinvent (2000), CH
	Concrete	Construction of store	3,000 m ³		Own estimate	Ecoinvent (2001), CH [†]
	Electricity	Running storage facility	25,000 GJ	0.5 TJ/year ^f	Chan et al. (1998)	Ecoinvent (2002), UK
	Water	Running storage facility	50,000 tonnes	1,000 m ³ /year for 50 years	Own estimate	Ecoinvent (2000), Eur

Table 3 (continued)

Life cycle stage	Process/tool/material	Use	Quantity	Assumptions	Source	LCA data source (age), region ⁱ
Land remediation	Excavation	Soil movement	60,000 m ³	Double the soil stockpile for landscaping	Magnox Electric (2005)	Ecoinvent (2001), Eur
Transport	Freight transport (road)	Packaged waste to disposal site (assuming a distance of 300 km)	6.64 × 10 ⁷ tkm	300 km × 30 tonnes per package × 824 packages	Own estimate	Ecoinvent (2005), Eur
	Freight transport (rail)	Packaged waste to disposal site (assuming a distance of 1 km)	18,000 tkm	1 km × 30 tonnes per package × 6,357 packages	Own estimate	Ecoinvent (2000), Eur

^a Data for 2004/2005 from a Strategic Environmental Assessment at Trawsfynydd (NDA 2010a) are extrapolated for the 20-year retrieval period only, as demolition implicitly accounts for these activities

^b To decommission and package 16 tonnes of vessels and 5 tonnes of piping in a small nuclear facility required a total of 575 m of cuts, which has been scaled up for a 30,000 tonne steel volume and energy use calculated according to a reported cutting rates of 5–10 cm/min (IAEA 2001)

^c This has been scaled to last only 5 years as graphite retrieval is not expected to take the 10 years assumed in defining the basic decommissioning resource

^d Based on up to 20,000 tonnes already recovered from plant (Parsons 2007) plus additional boilers and construction use (approximately 10,000 t). Assumes 900 kg of steel is produced per tonne steel recycled

^e Figures are scaled up by the ratio of the concrete volumes in (Dones et al. 2009) and the Trawsfynydd ILW: 8,300–13,333 m³

^f Based on 1–2 W/m³, typical of underground car parks (Chan et al. 1998); around 5 % of the 13 TJ used annually at the Drigg LLW repository (NDA 2010b)

ⁱ LCA data considered applicable to UK, Switzerland (CH), Europe (Eur) or global (GLO) cases

^j Swiss production data amended to account for UK electricity mix in steel and concrete production

by wiping or washing with water, detergents or alcohol. Estimated requirements for Trawsfynydd steel are given in Table 3. More aggressive decontamination by blasting or chemical treatment (NEA 1999) could allow for either reuse or waste reclassification (i.e. cleaning ILW to create LLW). Such methods may eventually be used during final dismantling on the more contaminated metals forming the reactor core, but presently, this is expected simply to be disposed of as untreated waste.

Concrete in the fuel cooling ponds is decontaminated by scabbling. For decommissioning, the ponds have been sealed with a roof and fitted with ventilation and appropriate safety systems (see Table 2), while scabbling is performed using two remotely controlled vehicles (Brokks). Work commenced in 2005 and is ongoing, with refinement of methods and periodic replacement of equipment, e.g. the pond ventilation system (Madog-Jones 2006) and the scabbling heads and crane (Magnox North 2009a). Scabbling thus appears to require a similar range of typical equipment and resources for decommissioning as described for waste retrieval (see Table 2) so these data have been used to characterise scabbling in the LCA model (see Table 3). There are no plans to decontaminate any other structural concrete prior to disposal as LLW after demolition.

Graphite retrieval is currently expected to resemble other retrieval operations, in so far as requiring remotely operated heavy machinery under similar containment measures and hence is also represented by the typical equipment and resources for decommissioning. Current plans are to package and dispose of graphite as ILW, but alternative treatments and waste reduction methods are currently sought (von Lensa et al. 2008). Despite the likelihood of change, it is assumed here that disposal will proceed according to the current plan.

3.4.2 Construction and demolition

Throughout decommissioning, construction work is required to provide access or exit pathways, new temporary buildings or other infrastructure in which to carry out various decommissioning operations, e.g. lowering the reactor roof at Trawsfynydd in preparation for the care and maintenance period. Construction material use has been estimated using data from the Strategic Environmental Assessment of Trawsfynydd (NDA 2010a); these data are shown in Table 3.

Following the care and maintenance period, all power plant buildings and remaining temporary structures will be demolished. As residual radioactivity will have diminished to safe levels, demolition will only require standard construction methods. However, since the reactor structure is specifically designed to resist destruction, demolition may require considerably more energy than a similarly sized standard building (see Table 3).

Table 4 Summary of data for different decommissioning stages used in the LCA model (based on the data in Tables 1, 2 and 3)

	Project life (years)	Total electricity use (TJ)	Mean annual electricity use (TJ)	Total water use (m ³)	Mean annual water use (m ³)	Total steel use (t)	Total concrete use (t)	No. of ILW packages	No. of LLW packages
Site management	30	87.30	2.91	225,000	7,500	—	—	0	0
Plant deconstruction	—	—	—	—	—	—	—	92	6,032
Scabbling	10	3.77	0.42	9,300	930	—	—	4	118
Cutting	10	5.08	0.51	9,300	930	—	—	—	—
Graphite retrieval	5	1.89	0.42	4,650	930	—	—	211	3
Decontamination	20	7.19	0.36	8,805	880	—	—	—	—
Civil Engineering	20	9.69	0.48	—	—	3,000	2,250	—	—
Waste retrieval	—	—	—	—	—	—	—	—	—
MAC	10	3.77	0.42	9,300	930	—	—	20	0
FED	10	3.77	0.42	9,300	930	—	—	115	0
Sludge	10	3.77	0.42	9,300	930	—	—	6	0
Resins	10	3.77	0.42	9,300	930	—	—	0	6
AWV	10	3.77	0.42	9,300	930	—	—	376	38
R&D	30	1.52	0.05	—	—	—	—	—	—
Land remediation	—	—	—	—	—	—	—	0	360
Waste packaging	—	—	—	—	—	—	—	—	—
ILW	—	11.81	—	—	—	1,892	100,116 ^b	—	—
LLW	—	1.48	—	—	—	26,036	12,162 ^b	—	—
ILW management	—	—	—	—	—	—	—	—	—
Interim storage	—	25.97	0.5	—	—	2,000	32,000	—	—
Repository	—	25	0.5	—	—	—	—	—	—
LLW management	—	—	—	—	—	—	—	—	—
Total	—	200	—	303,555	15,820	32,928	146,528	824 ^c	6,557 ^c

^a Total reported energy consumption in 2007 was 7 TJ/year (NDA 2010b). For comparison, consumption at some other decommissioning Magnox plants was: Hunterston A—0.8 TJ in 2004 and 17 TJ in 2007; Hinkley Point—30 TJ in 2007; and Bradwell—19 TJ in 2007 (NDA 2010c; NDA 2010d; NDA 2010e). This is because decommissioning activities at each site vary considerably

^b Each box is assumed to contain a standard volume of concrete grout: 8.48 m³ for LLW (Entec 2010) and 8.2 m³ for ILW

^c Total volume of ILW=13,400 m³; total volume of LLW=60,700 m³

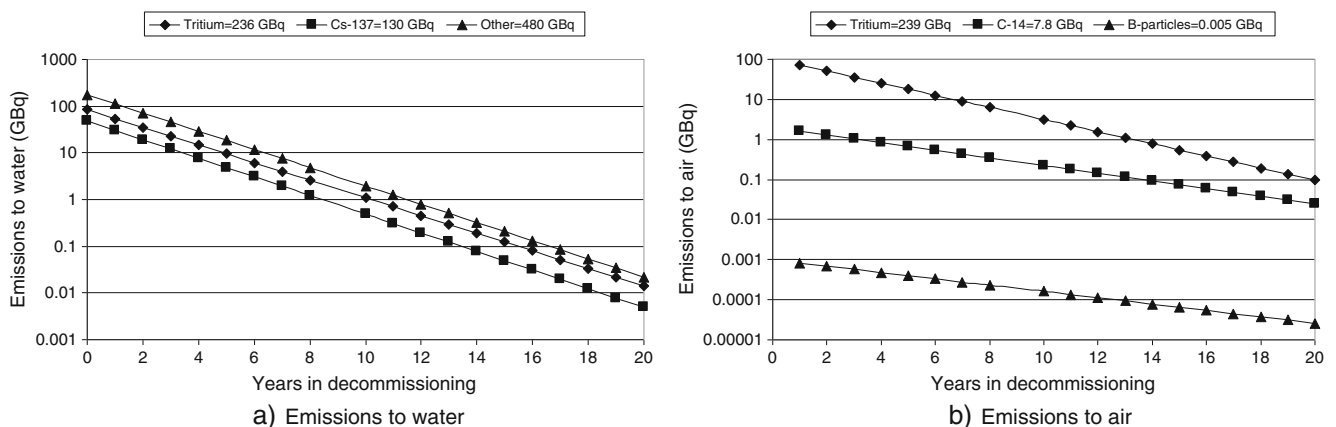


Fig. 3 Radioactive emissions to water and air from closed Magnox power stations Magnox Electric (2005). Total emissions over the decommissioning period are shown in the legend

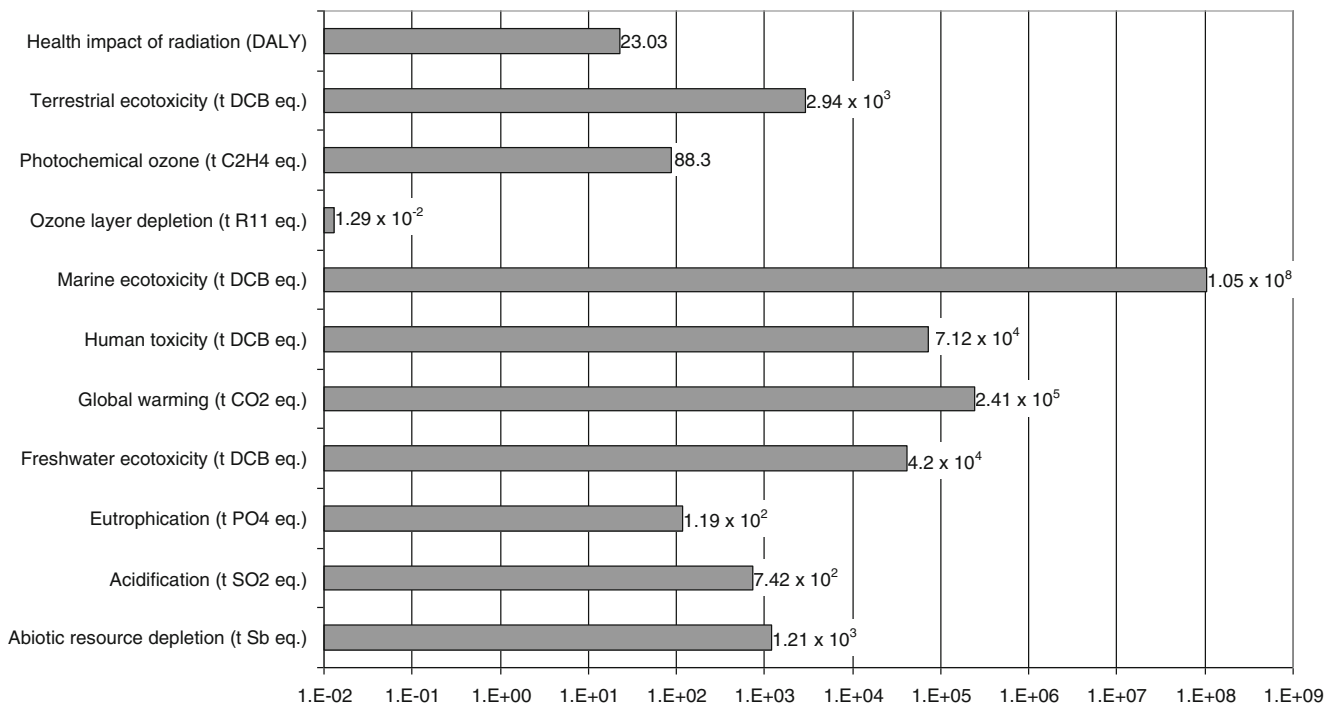


Fig. 4 Total environmental impacts of decommissioning of Trawsfynydd over the lifetime of the decommissioning process. The results shown in the figure are the rounded off total results in tonnes shown in Table 5

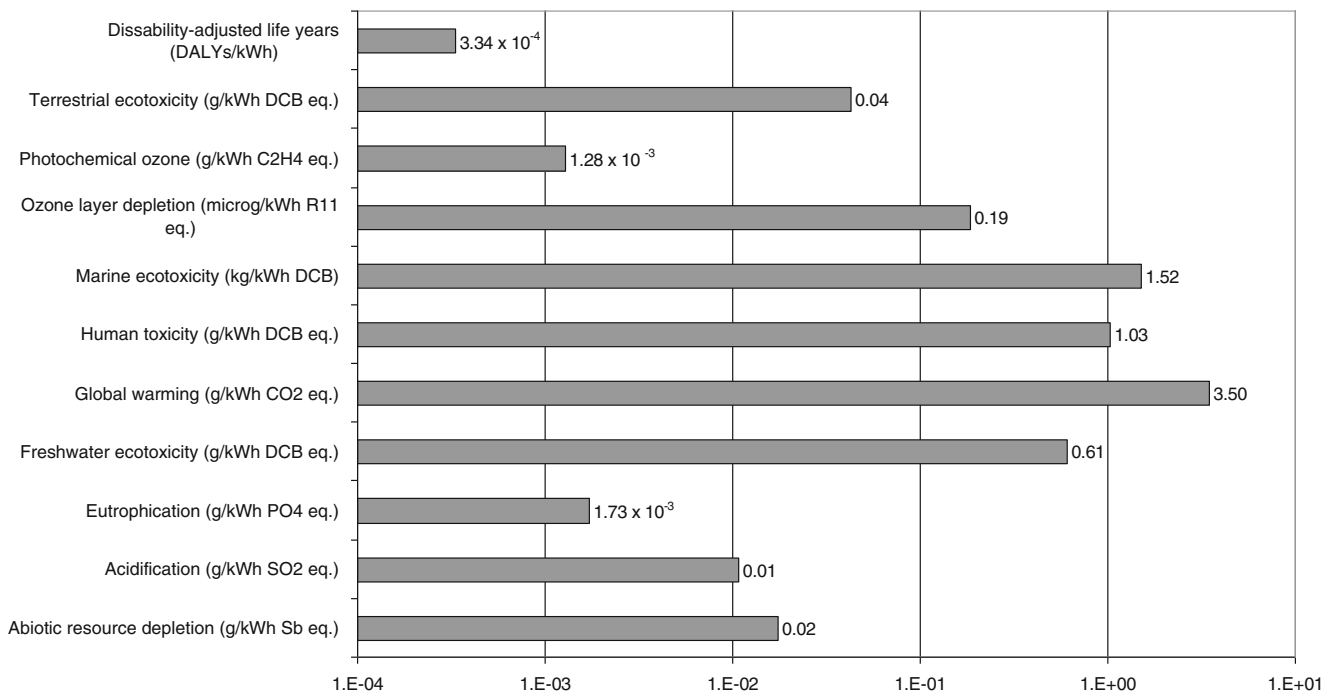


Fig. 5 Environmental impacts of decommissioning expressed per kilowatt hour of electricity generated by the Trawsfynydd power plant over its useful lifetime (69 TWh). The results shown in the figure are the rounded off results per kilowatt hour shown in Table 5

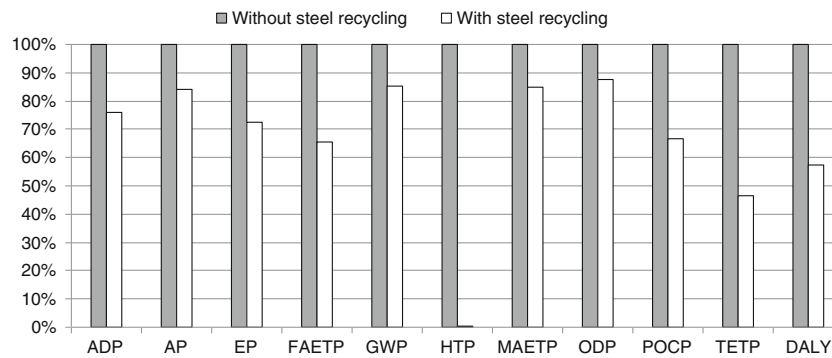


Fig. 6 Sensitivity analysis: effect of steel recycling on the impacts from decommissioning. Percentage of total steel recycled: 70 %. The system has been credited for the avoided impacts from the equivalent amount of ‘virgin’ steel using the Ecoinvent data, which are based on

the European mix of ‘virgin’ steel production consisting of 63 % primary steel and 37 % recycled steel. For full names of impact categories, see Table 5

3.5 Land remediation

There is an estimated 9,500 m³ of radiologically contaminated soil at Trawsfynydd (NDA 2010a). Currently, this is expected simply to be dug up and packaged for disposal as radioactive waste (see Fig. 2); hence, this stage is characterised as excavation works (see Table 3).

3.6 Recyclable materials

Although recyclable materials are being recovered during the decommissioning process (Parsons 2007), no recycling is considered in this study as it is not clear at this stage if and how much will actually be recycled. However, the potential effect of steel and concrete recycling on the total impacts are considered as part of the sensitivity analysis, by crediting the system for avoiding the impacts from virgin steel and concrete, respectively. As previously mentioned and shown

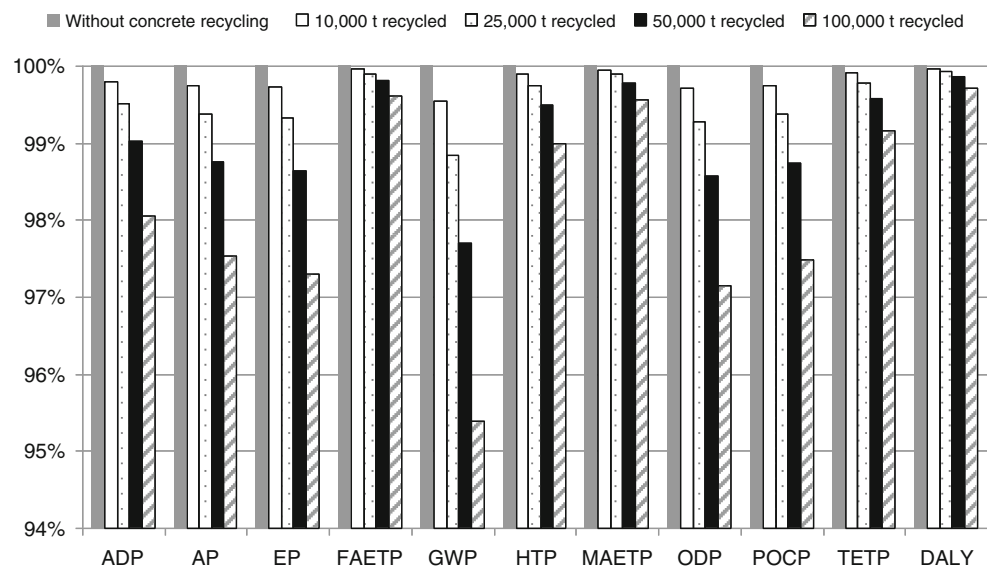
in Table 3, a total of 30,000 tonnes of steel is assumed to be available for recycling—this represents approximately 70 % of the estimated 43,500 t of steel embodied in the plant (see Section 3.4.1).

The total amount of concrete at a nuclear power plant is estimated at around 160,000 t (see Section 3.4.1), with half of that arising from deconstruction of temporary structures (see Table 3). However, it is not clear how much of the total amount of concrete could be recycled so the sensitivity analysis considers a range between 10,000 and 100,000 t, assuming that not all of the concrete would be available for recycling. The results of the sensitivity analysis are presented in Section 4.

3.7 Packaged waste

Conditioned nuclear wastes are packaged in various containers appropriate to their form and level of radioactivity and

Fig. 7 Sensitivity analysis: effect of concrete recycling on the impacts from decommissioning. The system has been credited for the avoided impacts from the equivalent amounts of virgin concrete. For full names of impact categories, see Table 5



suitable for long-term storage or disposal. These are generally steel boxes or drums, possibly lined with concrete and then also possibly placed within a concrete ‘overpack’. Drums may be crushed into ‘pucks’ and placed into larger boxes. Containers are filled with ‘grout’ (usually concrete) to immobilise and separate the wastes. The UK radioactive waste inventory (NDA 2007) has been used to calculate the cumulative resource requirements for packaging all expected wastes from Trawsfynydd (Table 4).

To simplify calculations, the number of waste packages generated by each decommissioning activity (see Table 4) is based solely on the steel volume needed for packaging. A typical waste package is defined for LLW (one package requiring 2.2 t of steel) and another for ILW (one package requiring 4.2 t of steel). For the volume of waste and cement grout in each package, a typical average value is assumed (see Table 4). Each ILW package is also assumed to contain 150 kg of secondary wastes, i.e. material contaminated in decommissioning, such as latex gloves, air filters, tools and paper towels (NDA 2007).

3.8 Interim storage

Currently, ILW is packaged at each decommissioning site and then stored in temporary surface storage. Trawsfynydd’s newly built temporary storage will eventually be demolished once a final disposal facility becomes available for the UK (see Section 3.9). Data used for storage and disposal can be found in Tables 3 and 4.

3.9 Final disposal

Trawsfynydd waste arisings make up 5 % of UK’s current legacy waste and are estimated to be 13,200 m³ of packaged ILW and 72,900 m³ of packaged LLW (Defra and NDA 2007). This waste will eventually be disposed of in a deep geological disposal facility, together with all other UK HLW and ILW waste. At present, no finalised designs for waste disposal exist, but it is expected that a disposal facility will be developed by around 2040. However, the location and final design are not yet known so that no data are available. The extant UK generic repository design studies (Nirex 2003) indicate that a dedicated ILW repository will be approximately 600 m below ground, which, in terms of size and depth (and hence engineering requirements), is similar to the Swiss design. Therefore, the data for the Swiss repository in clay-based rocks (Dones et al. 2009) have been used and scaled for the amount of ILW waste from Trawsfynydd; for details, see Table 4.

It is also assumed that transport of all packaged waste from Trawsfynydd to final disposal will be by road, with a short rail transfer (see Table 3). Distances of 300 km by road and 1 km by rail have been assumed.

Table 5 Environmental impacts over the life cycle of decommissioning showing contribution of different life cycle stages

	Abiotic depletion potential (ADP) (t Sb eq.)	Acidification potential (AP) (t SO ₂ eq.)	Eutrophication potential (EP) (t PO ₄ eq.)	Freshwater aquatic ecotoxicity potential (FAETP) (t DCB eq.)	Global warming potential (GWP) (t CO ₂ eq.)	Human toxicity potential (HTP) (t DCB eq.)	Marine aquatic ecotoxicity potential (MAETP) (Mt DCB eq.)	Ozone layer depletion potential (ODP) (kg R11 eq.)	Photochemical ozone creation potential (POCP) (t C ₂ H ₄ eq.)	Terrestrial ecotoxicity potential (TETP) (t DCB eq.)	Health impact of radiation (DALY)
Site management	121	61.377	6.628	671.807	15,041	2,087	10,546	0.536	4.328	42.76	0.181
R&D	1.076	0.617	0.072	13.121	151	40.189	92.744	0.005	0.047	1.016	0.004
Waste retrieval	49.1	28.107	3.922	1,032	10,023	1,579	3743.57	0.418	2.684	75.51	0.113
Plant deconstruction	480	293	49.615	18,435	124,005	16,640	36,575	6.175	34.27	1,265	17.21
LLW disposal	33.393	17.684	1.952	96,863	5,336	474.6	2421.25	0.165	1.362	8,628	0.050
ILW storage and disposal	447	288	44.895	20,598	72,376	48,812	48,841	3.958	37.56	1,466	5.299
Land remediation	24,040	14,919	2,568	830,434	6,591	789	1650.378	0.329	1.786	54.98	0.042
Transport	56.704	37.648	9.663	321,894	7,746	746,549	869,795	1.269	6.282	22.84	0.136
Total	1,212 t	741 t	119 t	41,999 t	241,269 t	71,168 t	104,740 t	12.86 t	88.32 t	2,937 t	23.04 DALY
Total per kWh electricity generated over the lifetime of power plant	1.76×10^{-2} g	1.07×10^{-2} g	1.73×10^{-3} g	0.61 g	3.50 g	1.03 g	1,518 g	1.86×10^{-7} g	1.28×10^{-3} g	4.26×10^{-2} g	3.34×10^{-10} DALY

3.10 Radioactive emissions from decommissioning

At around 1 % of permitted limits, radioactive emissions from decommissioning are far lower than from an operating Magnox plant (Magnox Electric 2005). The most significant aqueous nuclides, deriving from decontaminating fuel cooling ponds and processing and packaging of ILW, are tritium and cesium-137. Aerial discharges diffusing from the reactor core are also relatively low but include tritium, carbon-14 and beta particles. Levels vary significantly with decommissioning activity.

Radioactive emissions to water and air from decommissioning several Magnox sites are plotted in Fig. 3. As can be seen, most of the emissions occur in the first 20 years of decommissioning; these data have been used to estimate the impacts from radiation (see next section). The emissions from the LLW and ILW repositories are negligible (Bayliss and Langley 2004; LLWR Repository and NDA (2012) and have therefore not been considered in this study.

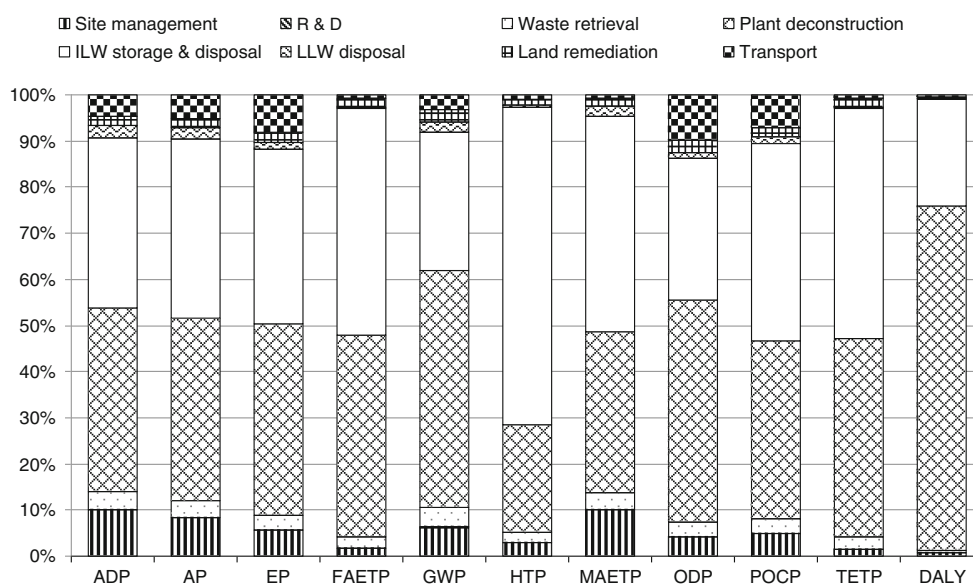
4 Impact assessment and interpretation of results

The study follows the ISO 14040/44 LCA guidelines (ISO 2006a; ISO 2006b). The LCA software Gabi v4.4 (International 2011) has been used for modelling the system and estimating the environmental impacts following the CML 2001 methodology (Guinée et al. 2001). The Ecoinvent (2011) database has been used for the background LCA data for the UK conditions (see Tables 1, 2 and 3 for details).

The total impacts over the lifetime of decommissioning, assuming no recycling of recyclable materials, are shown in Fig. 4; the impacts per kilowatt hour of electricity generated

by the power plant during its useful lifetime (69 TWh) are given in Fig. 5. For example, the total global warming potential (GWP) is estimated at 241 kt CO₂ eq., equating to 3.5 g CO₂ eq./kWh. By comparison, the GWP values reported by previous studies for the whole life cycle of nuclear power range from 1 to 527 g CO₂ eq./kWh, but the vast majority report 5–10 g CO₂ eq./kWh (Weisser 2007; Fthenakis & Kim 2007; Lenzen 2008). Taking the latter range as a basis would suggest that the contribution of decommissioning to the whole nuclear life cycle GWP, as estimated in the present study, is significant. This agrees well with the findings of Voorspools et al. (2000) who report the GWP from decommissioning in the range of 2–4 g CO₂ eq./kWh despite, like here, not considering the spent fuel within the system boundary. However, other studies (White & Kulcinski 2000; Weisser 2007; Sovacool 2008; Vattenfall 2010a; Vattenfall 2010b) report lower GWP values for decommissioning, ranging between 0.01 and 1.4 g CO₂ eq./kWh. There could be a number of reasons for the difference in the results between different studies, including not only different assumptions, reactors considered and data used but also the level of detail at which this part of the life cycle of nuclear power has been assessed. As far as the authors are aware, this is the first study to consider decommissioning of nuclear plants in as much detail, and particularly for Magnox plants, which may explain the higher GWP results compared to other, less detailed, studies of decommissioning. Furthermore, most studies consider a generic case of a 1,000-MW pressurised water reactor (PWR) from the 1970s, with an assumed lifetime of 40 years and an operating capacity of 80–85 %, whereas different sites and reactors have unique operational and decommissioning histories. For example, the lifetime electricity output of Trawsfynydd was only 30 % of the typical generic values assumed in other studies, which translates to three to four times higher impacts per kilowatt hour of

Fig. 8 The relative contribution of different decommissioning stages to the overall environmental impacts. Waste retrieval and Plant deconstruction include the packaging of the wastes. For the full names of impact categories, see Table 5]



electricity generated. In addition, decommissioning of the Trawsfynydd plant is expected to produce waste volumes five to six times greater than decommissioning of the UK's only PWR reactor at Sizewell B (NDA 2010f). Therefore, varied lifetime outputs of legacy plants (Fig. 6) as well as the amounts of waste can make comparisons between different plants difficult.

Furthermore, recycling of materials such as concrete and steel can also affect the results, as shown in Figs. 6 and 7. For example, assuming that 70 % or 30,450 t of steel is recycled (as mentioned in Section 3.6), reduces GWP by 15 % and human toxicity potential (HTP) by more than 99 %. Recycling of concrete, e.g. in packaging for radioactive waste, leads to more modest reductions in the environmental impacts. For instance, by recycling the maximum amount of 100,000 t of concrete assumed available for recycling, the average reduction of all impacts is just under 2 % with the greatest reduction of 4.6 % achieved for GWP. The modest savings are due to the need to crush the concrete before it can be re-used in packaging and the impacts associated with this activity.

Comparison with literature for the other impacts from decommissioning is difficult as other studies either consider only GWP or do not provide enough detail to allow meaningful comparisons.

As indicated in Table 5 and Fig. 8, most impacts from decommissioning are due to the plant deconstruction (25–75 %) and ILW storage and disposal (25–70 %). Around 85 % of the impacts from deconstruction of the plant are due to the steel and concrete used to package the LLW and ILW wastes. Construction of the repository accounts for 90 % of the impacts from ILW storage and disposal. Site management and transport contribute between 1 and 10 % to the impacts, while waste retrieval (up to 4 %), R&D (up to 1 %), LLW disposal and land remediation (up to 3 % each) have relatively low impacts.

The exception to this trend is the health impact of radiation as measured by disability-adjusted life years (DALYs)

Table 6 Magnox plants and their closure dates

Power station	Net power (MWe)	Operation started	Closure
Berkeley	276	1962	1989
Bradwell	246	1962	2002
Calder Hall	200	1959	2003
Chapelcross	240	1960	2004
Dungeness A	450	1965	2006
Hinkley Point A	470	1965	2000
Hunterston A	300	1964	1990
Oldbury	434	1968	2012
Sizewell A	420	1966	2006
Trawsfynydd	390	1965	1991
Wylfa	980	1972	2014

Table 7 Allocation of environmental impacts from Trawsfynydd per volume of waste as a basis for estimation of decommissioning impacts from other UK Magnox sites

	ADP	AP	EP	FAETP	GWP	HTP	MAETP	ODP	POCP	TETP	DALY
Total (t/fu.) ^a	1,212	741	119	41,999	241,269	71,168	104,740	12.86	88.32	2,937	23.04
ILW disposal (%) ^b	36.86	38.84	37.63	49.04	30.00	68.59	46.63	30.79	42.53	49.93	23.01
Waste retrieval and plant deconstruction (%) ^b	43.68	43.34	44.87	46.35	55.55	25.60	38.49	51.29	41.84	45.63	75.20
Packaging (85 % of the above; %) ^b	37.12	36.84	38.14	39.40	47.22	21.76	32.72	43.59	35.56	38.79	63.92
Other decommissioning activities (%) ^b	26.02	24.32	24.23	11.56	22.78	9.65	20.65	25.62	21.91	11.28	13.07
ILW disposal (kg/m ³ or DALY/m ³ of waste) ^c	33.35	21.51	3.35	1537.18	5401.21	3642.66	3,644.853	2.95E-04	2.80	109.44	3.95E-04
Packaging (kg/m ³ or DALY/m ³ of waste) ^c	6.07	3.69	0.61	223.31	1537.43	208.99	462.489	7.56E-05	0.42	15.37	1.99E-04
Other decommissioning activities ^c (kg/m ³ or DALY/m ³ of waste)	4.26	2.44	0.39	65.51	741.83	92.72	291.878	4.44E-05	0.26	4.47	4.06E-05

^aThe results as shown in Table 5

^bThe results as shown in Fig. 8. Packaging contributes around 85 % to the total impacts from waste retrieval and plant deconstruction (see Section 4)

^cAn example calculation for GWP for Trawsfynydd: $\text{GWP due to ILW disposal} : 241,269(\text{total GWP, tCO}_2 \text{ eq.}) \times 0.3(\text{contribution of ILW disposal}) / 13,400(\text{m}^3 \text{ ILW}) = 5.4012 \text{ tCO}_2 \text{ eq./m}^3 = 5401.2 \text{ kg CO}_2 \text{ eq./m}^3$; $\text{GWP due to packaging} : 241,269(\text{total GWP, tCO}_2 \text{ eq.}) \times 0.47(\text{contribution of packaging}) / 74,100(\text{m}^3 \text{ LLW} + \text{ILW}) = 1.5374 \text{ tCO}_2 \text{ eq./m}^3 = 1537.4 \text{ kg CO}_2 \text{ eq./m}^3$; $\text{GWP due to other decommissioning activities} : 241,269(\text{total GWP, tCO}_2 \text{ eq.}) \times 0.228(\text{contribution of other decommissioning activities}) / 74,100(\text{m}^3 \text{ LLW} + \text{ILW}) = 0.748 \text{ tCO}_2 \text{ eq./m}^3 = 741.83 \text{ kg CO}_2 \text{ eq./m}^3$

Table 8 Potential environmental impacts of decommissioning the UK Magnox reactors^a

Magnox site	Lifetime output (TWh)	ILW arising ^b (m ³)	LLW arising ^b (m ³)	ADP (g Sb eq./kWh)	AP (g SO ₂ eq./kWh)	EP (g PO ₄ eq./kWh)	FAETP (g DCB eq./kWh)	GWP (g CO ₂ eq./kWh)	HTP (g DCB eq./kWh)	MAETP (g DCB eq./kWh)	ODP (μg R11 eq./kWh)	POCP (g C ₂ H ₄ eq./kWh)	TETP (g DCB eq./kWh)	DALY (DALY/kWh)
Berkeley ^c	43	6,910	30,300	0.014	0.009	0.0014	0.497	2.840	0.846	1,239	0.151	0.0010	0.035	2.71×10^{-10}
Bradwell	60	5,770	51,400	0.013	0.008	0.0013	0.423	2.691	0.638	1,069	0.143	0.0009	0.029	2.66×10^{-10}
Calder Hall	60	9,410	51,000	0.016	0.010	0.0015	0.532	3.142	0.875	1,331	0.167	0.0011	0.037	3.03×10^{-10}
Chapelcross	60	6,230	167,000	0.033	0.020	0.0032	0.993	7.141	1.249	2,556	0.377	0.0023	0.069	7.32×10^{-10}
Dungeness A	115	6,940	34,900	0.006	0.004	0.0006	0.198	1.155	0.330	494	0.062	0.0004	0.014	1.11×10^{-10}
Hinkley point A	103	7,270	57,400	0.009	0.005	0.0009	0.290	1.812	0.447	731	0.096	0.0006	0.020	1.78×10^{-10}
Hunterston A	74	8,350	57,600	0.013	0.008	0.0013	0.431	2.641	0.680	1,084	0.140	0.0009	0.030	2.58×10^{-10}
Oldbury	125	6,120	32,900	0.005	0.003	0.0005	0.165	0.976	0.273	414	0.052	0.0004	0.012	9.41×10^{-11}
Sizewell A	110	6,140	38,700	0.006	0.004	0.0006	0.204	1.231	0.326	511	0.065	0.0004	0.014	1.20×10^{-10}
Trawsfynydd ^d	69	13,400	60,700	0.018	0.011	0.0017	0.609	3.497	1.031	1,518	0.186	0.0013	0.043	3.34×10^{-10}
Wylfa	225	8,430	59,500	0.004	0.003	0.0004	0.145	0.890	0.228	364	0.047	0.0003	0.010	8.71×10^{-11}
Average				0.012	0.008	0.001	0.408	2.547	0.629	1,028	0.135	0.001	0.028	2.50×10^{-10}
Total	1,044 TWh	84,970 m ³	641,400 m ³	10,298 t	6,465 t	1,016 t	340,474 t	2,114,384 t	528,862 t	752,920,740 t	99,329 t	725 t	23,722 t	207 DALY

^a Extrapolated based on the findings for Trawsfynydd presented in Section 4^b NDA (2010f)^c Example calculation of GWP for Berkeley: $\text{GWP due to ILW disposal} : 5401.2 \text{ kg CO}_2 \text{ eq./m}^3 \times 6910 \text{ m}^3 \text{ ILW} = 37,322 \text{ t CO}_2 \text{ eq.}$; $\text{GWP due to packaging} : 1537.4 \text{ kg CO}_2 \text{ eq./m}^3 \times (6910 + 30,300) \text{ m}^3 \text{ LLW} + \text{ILW} = 57,207 \text{ t CO}_2 \text{ eq.}$; $\text{GWP due to other decommissioning activities} : 741.83 \text{ kg CO}_2 \text{ eq./m}^3 \times (6910 + 30300) \text{ m}^3 \text{ LLW} + \text{ILW} = 27,603 \text{ t CO}_2 \text{ eq.}$; Total GWP: $(37,322 \text{ t CO}_2 \text{ eq.} + 57,207 \text{ t CO}_2 \text{ eq.} + 27,603 \text{ t CO}_2 \text{ eq.}) \times 1,000,000 \text{ g/43,000,000,000 kWh} = 2.84 \text{ g CO}_2 \text{ eq./kWh}$ ^d Environmental impacts as shown in Table 5; a slight difference due to rounding off

where plant deconstruction is the main contributor (75 %). The next largest contributor is ILW storage and disposal (23 %); the other life cycle stages have negligible impact. The majority of radioactive releases contributing to this impact occur during the decommissioning work. However, a significant proportion of the health impact from radiation (around 25 %) is due to the ‘background’ radioactive releases, including steel and concrete manufacture, power generation and, most importantly, excavating the repository during which the naturally occurring radioactive emissions are released. The latter should be considered when designing and building the repository in order not to counterbalance the efforts for containing anthropogenic radioactive waste.

With respect to the repository, its estimated contribution to the impacts should be treated with caution as the data are based on the Swiss repository design (see Section 3.9). Although the UK design is expected to be similar, the Swiss repository is housed in clay rocks, but potential alternatives to clay for the UK also include sites with hard crystalline rocks or salt. Each rock type presents different construction challenges, which could lead to different resource consumption and therefore the environmental impacts from this life cycle stage. In addition, the Swiss design is a co-located repository for HLW and ILW (Dones et al. 2009), whilst the UK generic design studies refer to a potential dedicated ILW repository (Nirex 2003). This could alter the scaling and allocation assumptions, again changing the overall impacts. However, despite this uncertainty, the volumes of rock removed and structural engineering required for the Swiss design are likely to be representative of the UK repository. Thus, the results reported here should provide a meaningful baseline, in the context of the wider uncertainties inherent in a decommissioning process, which extends over the whole of the next century (some of which are also addressed in Section 6).

5 Potential impacts of decommissioning the UK fleet of Magnox power plants

Given that the UK has 10 Magnox plants in addition to Trawsfynydd that will need to be decommissioned over

the next decades (Table 6), this section considers the potential impacts of their decommissioning by extrapolating the LCA results estimated for Trawsfynydd. Because the majority of the impacts depend directly on the volume of waste, determining how much packaging and repository volume for disposal is required, the extrapolation is based on the expected ILW and LLW waste arisings from these plants estimated by NDA (2010f). Table 7 shows the basis used for the extrapolation of the impacts and Table 8 specifies the waste volume data for the whole UK Magnox fleet.

As shown in Table 7, to estimate the impacts from decommissioning of other UK Magnox sites the total environmental impacts from Trawsfynydd have first been estimated per volume of waste for three types of decommissioning activity: ILW disposal, packaging of LLW and ILW waste, and the remaining decommissioning activities. These values have then been multiplied by the volumes of waste for each decommissioning site. An example calculation for GWP is shown below Tables 7 and 8; the latter also shows the results of extrapolation of the environmental impacts for all the sites.

Using GWP as an example, Fig. 9 shows a great variability in this impact for different sites, which ranges from 0.89 g CO₂ eq./kWh for Wylfa to 7.14 g CO₂ eq./kWh for Chapelcross. A similar trend is noticed for the other impacts (see Table 8). As suggested in Section 4, this variability is perhaps to be expected, since different sites generate different volumes of waste as well as energy outputs over their lifetime. However, it is the first time that such an estimate has been attempted confirming that the decommissioning impacts at different sites could be very different.

The results are yet different if the waste fuel generated at different Magnox sites and stored at Sellafield is also included in the estimates. Using the same method as above to allocate the Sellafield’s impacts amongst the different Magnox reactors according to the volume of waste generated at each site, the GWP of decommissioning increases on average by four times; in the case of Trawsfynydd, it goes up from 3.5 to 15.95 g CO₂/kWh (Fig. 10).

Overall, the results obtained here indicate that decommissioning of the UK Magnox reactors would generate in total around 2 Mt of CO₂ eq. (see Table 8). This would increase to

Fig. 9 Global warming potential of decommissioning the UK Magnox reactors

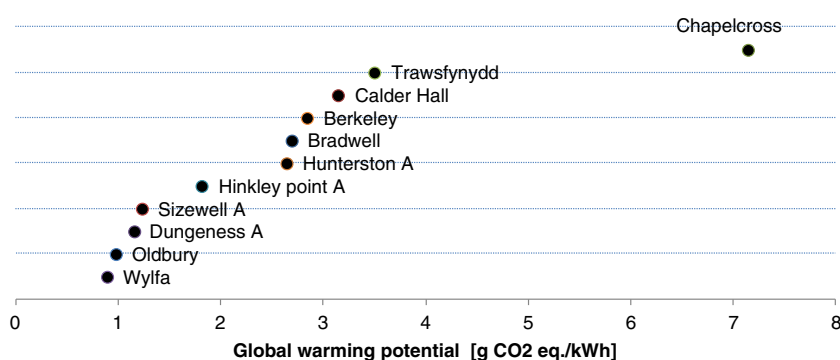
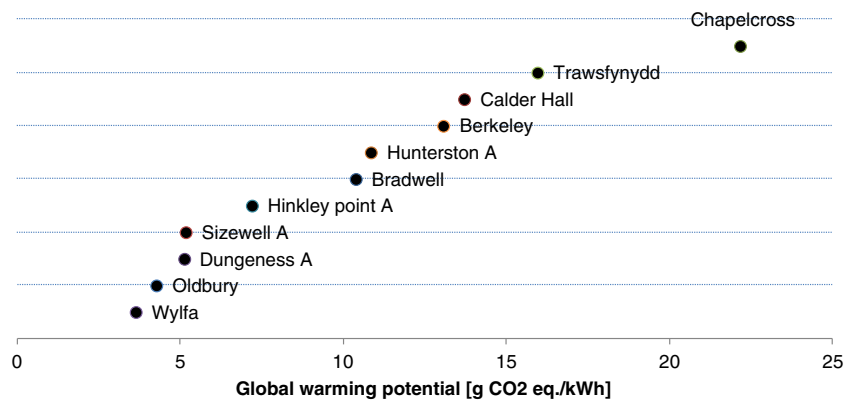


Fig. 10 Global warming potential of decommissioning the UK Magnox reactors including waste at Sellafield. Estimates based on the total amount of waste at Sellafield of 3.462 million m³



11 Mt of CO₂ eq. if the waste from Sellafield is included. To put these results in context, the UK annual GHG emissions in 2011 were around 549.3 Mt of CO₂ eq. (DECC 2012). Therefore, the GWP from decommissioning the UK Magnox legacy sites would contribute around 0.4 % to the total UK annual emissions without and 2 % with the Sellafield waste. This is assuming that the decommissioning process is completed within 1 year, which, of course, is not the case as it takes place over very long time periods (around 100 years) so the contribution to the GHG emissions from decommissioning per year would be much lower. Nevertheless, as the emissions of GHG are cumulative and GWP is estimated over 100 years, the overall contribution of decommissioning to climate change is arguably not negligible.

The long duration of decommissioning or even delaying it could potentially be advantageous in terms of the environmental impacts. For example, the GWP could potentially be reduced by delaying decommissioning to allow the energy system to be substantially decarbonised, as envisaged by the UK Government (2006). Figure 11 illustrates the

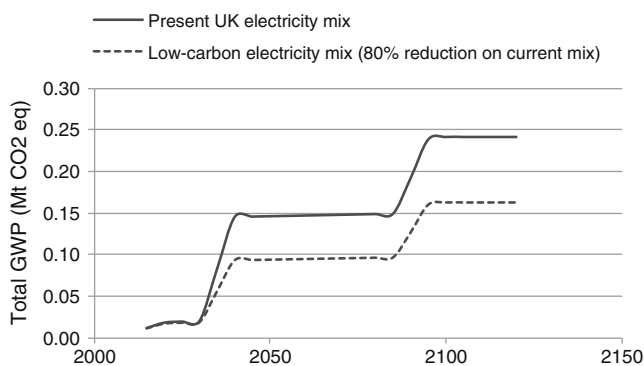


Fig. 11 Cumulative global warming potential of decommissioning the reactor at Trawsfynydd over time depending on the UK electricity mix. It is assumed that the carbon intensity of the UK electricity mix reduces from the current 500 to 50 g CO₂ eq./kWh by 2030. This is congruent with the UK Government's target of 80 % carbon reduction in the whole energy sector, which would require almost complete decarbonisation of the electricity sector

potential reduction in GWP from decommissioning the reactor at Trawsfynydd if the UK 2050 carbon reduction targets of 80 % were met (UK Government 2006). As indicated, the total GWP of 241 kt CO₂ eq. could potentially be reduced by 50 % by the end of the decommissioning process in around 2100 if the process was delayed to around 2030. Other impacts may also be reduced particularly as more advanced decommissioning methods become available through the ongoing R&D, but these should be assessed properly before drawing any conclusions. On the other hand, the benefits of early decommissioning include more rapid reduction of safety and environmental hazards and reduced short-term costs (although the long-term financial costs of waste management remain unknown). Therefore, there is a conflict between the potential environmental benefits of delay and the accelerated decommissioning at Trawsfynydd funded by the UK Nuclear Decommissioning Authority (NDA).

Furthermore, social aspects of decommissioning must also be taken into account before decisions are made on the decommissioning methods and the time scales. For example, delaying the decommissioning process would lead to further accumulation of waste requiring on-site storage, also risking accidental release of hazardous material into the environment. If it is eventually decided that all the waste should be stored in a single, central repository (which is the current preferred option in the UK), this would imply significant radioactive waste transport (of many tens of thousands of packages nationwide), which is an issue that the public objects to (see, e.g. Hall 2010). Any method aimed at segregating (and hence concentrating) waste to reduce the amount of packaging and therefore the environmental impacts also increases risk, possibly including security and nuclear proliferation concerns. Therefore, in addition to the environmental sustainability of decommissioning discussed here, economic and social assessment should be carried out to explore fully the sustainability implications of decommissioning the nuclear reactors in the UK.

6 Conclusions and recommendations

This paper has presented an in-depth analysis of life cycle environmental impacts of decommissioning the Magnox nuclear reactors in the UK. All stages in the life cycle of decommissioning have been considered, including site management, R&D activities, waste retrieval, plant deconstruction, packaging and storage of waste. The study is based on the case of Trawsfynydd reactor currently being decommissioned.

The GWP of decommissioning the whole plant is estimated at 241 kt CO₂ eq., equating to 3.5 g CO₂ eq./kWh of electricity generated during the lifetime of the plant. By comparison, typical GWP values reported in the literature for the whole life cycle of nuclear power are in the range of 5–10 g CO₂ eq./kWh, suggesting that the contribution of decommissioning as estimated in the present study is significant.

Recycling of concrete and steel could reduce the environmental impacts significantly. For example, if 70 % of steel embodied in the plant is recycled, GWP is reduced by 15 % and human toxicity potential by more than 99 %. The environmental benefits from recycling 60 % of concrete are more modest, with the greatest reduction of 4.6 % achieved for GWP; this is due to the impacts associated with its crushing before it can be re-used.

Most impacts from decommissioning are due to the plant deconstruction and ILW storage and disposal, each contributing on average around 40 % to the total. Site management and transport contribute on average 5.5 and 4 % to the total, while waste retrieval, R&D, LLW disposal and land remediation contribute little to the impacts (1.5–3 %). Around 85 % of the impacts from plant deconstruction are due to the steel and concrete used to package the LLW and ILW wastes. Construction of the repository accounts for 90 % of the impacts from ILW storage and disposal.

Therefore, as these results indicate, the majority of the impacts (over 80 %) from decommissioning are directly related to the amount of waste that needs to be packaged and stored. These results have been used to extrapolate the environmental impacts to the whole of the UK Magnox fleet and the results suggest a great variability in the impacts for different sites. For example, the GWP ranges from 0.89 to 7.14 g CO₂ eq./kWh; a similar trend is noticed for the other impacts. This is due to different volumes of waste and the energy output generated by different reactors.

If the impacts from storage of waste fuel generated at different Magnox sites and stored at Sellafield are also included in the estimates, the GWP of decommissioning increases on average by four times; in the case of Trawsfynydd, it goes up from 3.5 to 15.95 g CO₂/kWh.

Overall, decommissioning of the UK Magnox reactors would generate 2 Mt of CO₂ eq. without and 11 Mt of CO₂

eq. with the waste from Sellafield. This represents 0.4 and 2 % to the current total UK annual emissions, respectively.

The study also shows that delaying the decommissioning process to allow the energy system to decarbonise could reduce the environmental impacts. For instance, delaying until 2030 could reduce the GWP by 50 % by the end of the decommissioning process around 2100. Other technological improvements, both in the decommissioning process and in the background, are also likely to happen over the time that could potentially reduce the impacts from decommissioning. However, economic and social aspects of any delays should be assessed fully before making any such decisions.

Regardless of the timelines, the environmental impacts of decommissioning would be reduced substantially by reducing the volume of the waste to be disposed of through appropriate waste management strategies and increasing recycling of materials, particularly steel.

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